

I. Ciepał · B. Kłos · St. Kistryn · E. Stephan · A. Biegun · K. Bodek ·
A. Deltuva · E. Epelbaum · M. Eslami-Kalantari · A. C. Fonseca · J. Golak ·
V. Jha · N. Kalantar-Nayestanaki · H. Kamada · G. Khatri · Da. Kirillov ·
Di. Kirillov · St. Kliczewski · A. Kozela · M. Kravcikova · H. Machner ·
A. Magiera · G. Martinska · J. Messchendorp · A. Nogga · W. Parol ·
A. Ramazani-Moghaddam-Arani · B. J. Roy · H. Sakai · K. Sekiguchi · I. Sitnik ·
R. Siudak · R. Skibiński · R. Sworst · J. Urban · H. Witała · A. Wrońska · J. Zejma

Investigations of Few-Nucleon System Dynamics in Medium Energy Domain

Received: 30 September 2012 / Accepted: 28 December 2012 / Published online: 13 January 2013
© The Author(s) 2013. This article is published with open access at Springerlink.com

Abstract Precise and large set of cross sections, vector A_x , A_y and tensor A_{xx} , A_{xy} , A_{yy} analyzing powers for the $^1H(d, pp)n$ breakup reactions were measured at 100 and 130 MeV deuteron beam energies with the use of the SALAD and BINA detectors at KVI and Germanium Wall setup at FZ-Jülich. Results are compared with various theoretical approaches which model the three-nucleon (3N) system dynamics. The calculations are based on different two-nucleon (2N) potentials which can be combined with models of the three-nucleon force (3NF) and other pieces of the dynamics can also be included like the Coulomb interaction and relativistic effects. The cross sections data reveal sizeable 3NF and Coulomb force influence. In case of analyzing powers very low sensitivity to the effects was found and the data are well describe by 2N models only. At 130 MeV for A_{xy} serious disagreements appear when 3NF models are included into calculations.

This work was partially supplemented by the Polish 2008–2010 science funds as a research Project No. N N202 174635, by the Polish 2009–2011 science funds as a research Project No. N N202 034836 and by funding from Jagiellonian University within SET project. The project is co-financed by the European Union.

I. Ciepał (✉) · A. Biegun · K. Bodek · J. Golak · G. Khatri · St. Kistryn · A. Magiera ·
W. Parol · R. Skibiński · R. Sworst · H. Witała · A. Wrońska · J. Zejma
Institute of Physics, Jagiellonian University, Kraków 30059, Poland
E-mail: izabela.ciepal@uj.edu.pl
Tel.: +123-45-678910
Fax: +123-45-678910

B. Kłos · E. Stephan
University of Silesia, Katowice 40007, Poland

St. Kliczewski · A. Kozela · R. Siudak
Institute of Nuclear Physics, Kraków 31342, Poland

M. Eslami-Kalantari · A. Ramazani-Moghaddam-Arani · N. Kalantar-Nayestanaki · J. Messchendorp
Kernfysisch Versneller Instituut, Groningen, 9747 AA, The Netherlands

M. Eslami-Kalantari
Faculty of Physics, Yazd University, Yazd, Iran

A. Ramazani-Moghaddam-Arani
Faculty of Physics, University of Kashan, Kashan, Iran

Da. Kirillov · H. Machner · A. Nogga
Forschungszentrum Jülich, Institut für Kernphysik, Jülich 52425, Germany

1 Introduction

One of the key issues of modern nuclear physics is investigation of forces acting between nucleons. Properties of 3N systems at medium energies are determined by pairwise nucleon-nucleon (NN) interaction, which is a dominant component. The interaction models are created based on the meson exchange theory or phenomenology. These so-called realistic NN potentials, like CD Bonn, Nijmegen or Argonne AV18 are able to predict observables for 2N systems with very high precision. To test thoroughly these models, environment with more than just two nucleons is needed. The simplest and nontrivial one is the 3N system, which can be studied in details with the use of the deuteron breakup reaction. The reaction with its 3N final state offers very simple and unique laboratory in which even very subtle dynamical effects like the 3NF, Coulomb force or relativistic component can be studied.

The theoretical predictions of observables are obtained by means of rigorous solution of Faddeev equations. Other than realistic NN potentials and supplementing them with 3NF models (TM99 3NF or Urbana IX 3NF), the 3N system dynamics can be described within the coupled-channels (CC) approach [1]. This method is based on explicit treatment of a single Δ -isobar degrees of freedom, which generates also certain 3NF effects. Another alternative way comes from chiral perturbation theory (ChPT). Here, the nuclear potential is obtained in a way of a systematic expansion in terms of momentum variable, and the many-body interactions appear naturally at growing orders. The non-vanishing 3NF appears at the next-to-next-to-leading (NNLO) order [2,3], which is numerically fully developed. Within the CC formalism the Coulomb interaction was implemented into calculations for the first time [4]. Recently, a consistent theoretical treatment of phenomenological 3NF and Coulomb force has been achieved also for the AV18+UIX potential [5] that allows to investigate the role of both effects on the high level of accuracy. Moreover, the relativistic treatment of the breakup reaction in 3N system was developed for calculations using the NN potential [6] and this approach has been also extended for calculations including the 3NF [7].

To verify the model predictions the deuteron breakup reaction can be used as a valuable experimental tool. The final state of the reaction is complex enough to test different ingredients of few-nucleon system dynamics, appearing with varying strength in certain phase space regions.

E. Epelbaum

Institut für Theoretische Physik II, Ruhr-Universität Bochum, Bochum 44780, Germany

A. Deltuva · A. C. Fonseca

Centro de Física Nuclear da Universidade de Lisboa, Lisboa 1649-003, Portugal

H. Kamada

Department of Physics, Kyushu Institute of Technology, Kitakyushu 804-8550, Japan

V. Jha · B. J. Roy

BARC, Bombay 400 085, India

Da. Kirillov · Di. Kirillov · I. Sitnik

JINR, Dubna, 141980, Russia

M. Kravcikova

Technical University, Kosice 04101, Slovakia

G. Martinska · J. Urban

P. J. Safarik University, Kosice 04154, Slovakia

B. J. Roy

Universität Bonn, Bonn 53113, Germany

H. Sakai

University of Tokyo, Bunkyo, Tokyo 1130033, Japan

K. Sekiguchi

Tohoku University, Sendai 9808578, Japan

2 Experimental Setup

The $^1\text{H}(\mathbf{d}, pp)n$ breakup reactions were studied in different phase space regions with the use of three detection systems: the SALAD and BINA at KVI [8–11] and the Germanium Wall (GeWall) at FZ-Jülich [12]. Results of the analyzing powers were obtained with the use of the BINA and SALAD apparatuses at polarized deuteron beam energies of 100 and 130 MeV, respectively. The cross sections were measured using the SALAD and GeWall detectors at deuteron beam energy of 130 MeV. The BINA detector offered access to the almost full phase space, whereas the SALAD and GeWall setups covered only forward polar angles.

The SALAD detector consisted of a three-plane multi-wire proportional chamber (MWPC) and two layers of a segmented scintillator hodoscope: horizontal ΔE and vertical stopping E detectors. The acceptance of the setup covered the region of the polar angles from 12° to 40° and the full range of the azimuthal angles. The liquid hydrogen target was placed inside the scattering chamber. BINA apparatus was constructed as an upgraded version of SALAD and possessed two main parts called Wall and Ball. Wall inherited most parts and features from SALAD, covering the same angular range and built of the same MWPC and modified ΔE and E hodoscopes. The backward part is ball-shaped and consists of 149 phoswich detectors which cover polar angles between 40° and 160° . The Ball plays two roles: of particle detector and scattering chamber. In the measurements liquid targets LH_2 was used.

The GeWall setup at the Research Center in Jülich (FZJ) consisted of three high-purity semiconductor position sensitive germanium detectors. Two different types of the detectors were used: a thin transmission detector “Quirl” with an excellent spatial resolution used to determine the position and energy loss (ΔE detector) of the passing charged particles, and two thick energy detectors E1 and E2 with excellent energy resolutions. The angular acceptance of the apparatus was $5^\circ - 14^\circ$ for the polar and 2π for the azimuthal angles.

3 Results and Conclusions

New generation measurements of the $^1\text{H}(\mathbf{d}, pp)n$ breakup reactions in a wide phase space region provided a very rich set of differential cross sections, vector A_x , A_y and tensor A_{xx} , A_{xy} , A_{yy} analyzing powers.

The cross sections were obtained for about 80 [9] kinematical configurations, defined by the polar angles of the two outgoing protons, θ_1 , θ_2 , and their relative azimuthal angle φ_{12} , for the energy of 65 MeV/nucleon with the use of the SALAD apparatus. Moreover, additional set of the cross sections for the same beam energy were obtained for 145 geometries with the GeWall detector [12]. The elastic scattering process was measured simultaneously in each experiment and the data were used for the breakup cross sections normalization. The obtained results allowed to trace different aspects of the system dynamics: 3NF effects and influence of the Coulomb force.

The data measured at KVI [13] reveal quite sizeable 3NF effects and confirmed its importance for understanding of the three nucleon system dynamics. Inclusion of this additional force in the calculations leads generally to a better description of the cross sections.

In the kinematical region of small polar angles significant discrepancies between the measured and predicted cross sections were found [8]. The inconsistency was accounted for the Coulomb interaction. Recently, the Coulomb force was successfully implemented into calculations within CC framework [4]. Adding the electromagnetic component into the models does not essentially change the quality of the data description at large relative energies, however at the small values the observed discrepancies are almost totally removed [14]. The Coulomb force were studied in more details in dedicated experiment at FZJ [12], focused on a very narrow part of the phase space. Dependencies of χ^2 per degree of freedom (d.o.f.) as a function of the relative energy E_{rel} and pair of the polar angles θ_1 , θ_2 of the two protons were studied, see Fig. 1. In the case of very small E_{rel} (see Fig. 1, left panel) the Coulomb effects are extremely high and only the predictions containing the Coulomb component are able to reproduce the data in a correct way. The obtained dependency of χ^2 on different combinations of θ_1 , θ_2 (see Fig. 1, right panel) shows that with increasing $\Delta\theta = |\theta_1 - \theta_2|$ value the Coulomb effects play less important part in reproducing the experimental data. For high $\Delta\theta$ the Coulomb force influence is negligible.

The obtained results of the vector analyzing powers of the breakup reaction at 65 and 50 MeV/nucleon [11] are well reproduced by 2N calculations in the whole studied phase space. In case of the tensor analyzing powers certain discrepancies are observed. The theory predicts quite large effects of TM99 3NF, however there are configurations in which inclusion of the TM99 3NF lead to a worse agreement with the experimental data. Such discrepancies were found especially for A_{xy} tensor analyzing power. This suggests an existence of some

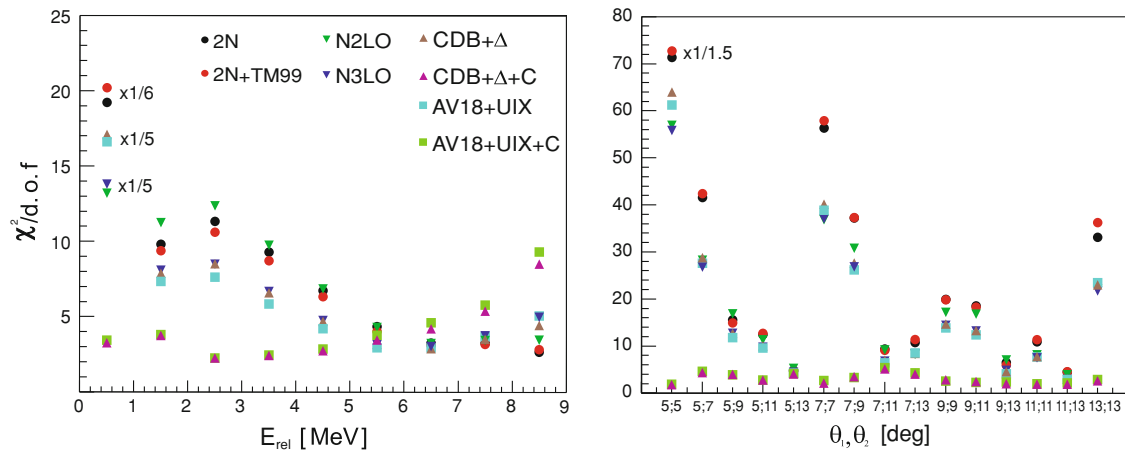


Fig. 1 Quality of description of the cross section data with the calculations based on various theoretical predictions, as indicated in the legend. Dependence of $\chi^2/\text{d.o.f}$ on the combination of kinetic energy of the relative motion (*left panel*) and the proton emission polar angles (*right panel*) of the two breakup protons are shown. Point with a very large value of $\chi^2/\text{d.o.f}$ is scaled down by factors, as indicated in the panel

missing ingredients in the spin part of the 3NF model. Moreover, the tensor analyzing powers A_{xy} measured at 50 MeV/nucleon reveal large effects of the Coulomb force for specific configurations.

4 Summary and Outlook

Precise and systematic studies of the breakup reaction in a large part of the phase space are very important for understanding of the interaction between nucleons in few-nucleon systems. Currently available theoretical approaches which try to model the interaction need very precise and large experimental database to be verified and further developed. Within these predictions different pieces of the dynamics can be studied separately and also their mutual interplay can be investigated. The obtained data in general confirmed the modern calculations, however there are still some problems with our understanding of the current models of the 3NF. Moreover, there is still strong need to have possibly complete theoretical treatments including all ingredients of the 3N system dynamics (3NF, Coulomb interaction, relativistic effects).

The future studies of the 3N system dynamics in the deuteron breakup reaction with the use of the WASA detector at FZJ are focused on investigation of the relativistic effects and the role of the 3NF at higher energies. Moreover, new scientific program concentrated on investigation of the few-nucleon systems dynamics at not too high energies was proposed to be carried out with the use of the BINA detector at the Cyclotron Center Bronowice in Cracow.

Open Access This article is distributed under the terms of the Creative Commons Attribution License which permits any use, distribution, and reproduction in any medium, provided the original author(s) and the source are credited.

References

1. Deltuva, A., Machleidt, R., Sauer, P.U.: Realistic two-baryon potential coupling two-nucleon and nucleon- Δ -isobar states: fit and applications to three-nucleon system. *Phys. Rev. C* **68**, 024005 (2003)
2. Entem, D.R., Machleidt, R.: Accurate nucleon-nucleon potential based upon chiral perturbation theory. *Phys. Lett. B* **524**, 93–98 (2002)
3. Epelbaum, E.: Few-nucleon forces and systems in chiral effective field theory. *Prog. Part. Nucl. Phys.* **57**, 645–741 (2006)
4. Deltuva, A., Fonseca, A.C., Sauer, P.U.: New calculations schemes for proton-deuteron scattering including the Coulomb interaction. *Phys. Rev. C* **73**, 057001 (2006)
5. Deltuva, A.: Momentum-space calculation of proton-deuteron scattering including Coulomb and irreducible three-nucleon forces. *Phys. Rev. C* **80**, 064002 (2009)
6. Skibiński, R., Witała, H., Golak, J.: Relativistic effects in exclusive neutron-deuteron breakup. *Eur. Phys. Jour. A* **30**, 369 (2006)

7. Witała, H., et al.: Three-nucleon force in relativistic three-nucleon Faddeev calculations. *Phys. Rev. C* **83**, 044001 (2011)
8. Kistryn, St., et al.: Systematic study of three-nucleon force effects in the cross section of the deuteron-proton breakup at 130 MeV. *Phys. Rev. C* **72**, 044006 (2005)
9. Kistryn, St., et al.: Evidence of the Coulomb-force effects in the cross sections of the deuteron-proton breakup at 130 MeV. *Phys. Lett. B* **641**, 23–27 (2006)
10. Stephan, E., et al.: Vector and tensor analyzing powers of elastic deuteron-proton scattering at 130 MeV deuteron beam energy. *Phys. Rev. C* **76**, 057001 (2007)
11. Stephan, E., et al.: Vector and tensor analyzing powers in deuteron-proton breakup at 130 MeV. *Phys. Rev. C* **82**, 014003 (2010)
12. Stephan, E., et al.: Three-nucleon interaction dynamics studied via the deuteron-proton breakup. *Int. Jour. Mod. Phys. A* **24**, 515–520 (2009)
13. Kalantar-Nayestanaki, N., et al.: Signatures of three-nucleon interactions in few-nucleon systems. *Rep. Prog. Phys.* **75**, 01,6301 (2012)
14. Kistryn, St., et al.: Cross sections of the deuteronw-proton breakup at 130 MeV: a probe of three-nucleon system dynamics. *Few-Body Syst.* **50**, 235–238 (2011)